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DRAFT FOR REVIEW

Traffic and Air Quality Impacts of Natural Gas Drilling

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Chapter 1. Introduction

Technological advances in drilling methods and techniques have allowed for the extraction of natural gas locked in tight, impermeable shale and have facilitated a dramatic increase in gas production from these *"unconventional"* gas reservoirs. These techniques involve horizontal drilling and hydraulic fracturing or "fraccing" – the process of pumping air, water, and sand under high pressure into the well hole to fracture through the thick shale and stimulate the flow of natural gas. The economic benefits of increased natural gas production from these hydrocarbon-rich shale formations are undeniable.

On the other hand, increased natural gas mining is impacting Texas's transportation system and more recently has resulted in concerns about the impacts on the environment - specifically the impacts on water resources and air quality. The contamination of surface water and drinking water wells, as well as excessive water use, are major concerns, while some have argued that the lifecycle emissions benefits – specifically greenhouse gas emissions benefits - of mining, distributing, and using natural gas have been overestimated. The impact of Volatile Organic Compounds (VOCs) and Oxides of Nitrogen (NOx) emissions – which are precursors to ground level ozone - from natural gas extraction on local and regional air quality are also of specific concern (*1*) as some of the shale formations in Texas are in areas of nonattainment (e.g., Dallas-Fort Worth) or near-nonattainment (e.g., Victoria). The concern is that intensive natural gas extraction can worsen the air quality in nonattainment areas, thereby impacting ongoing monitoring, or could result in areas of near-nonattainment becoming in violation of National Ambient Air Quality Standards. Air pollution concerns have thus resulted in the U.S. Environmental Protection Agency (EPA) issuing new regulations to reduce air pollution from the oil and natural gas industry on April 17, 2012. This report provides information about Texas's natural gas resources (Chapter 2), the elements of the natural gas supply chain and the environmental concerns associated with each element (Chapter 3), before concluding with some remarks (Chapter 4).

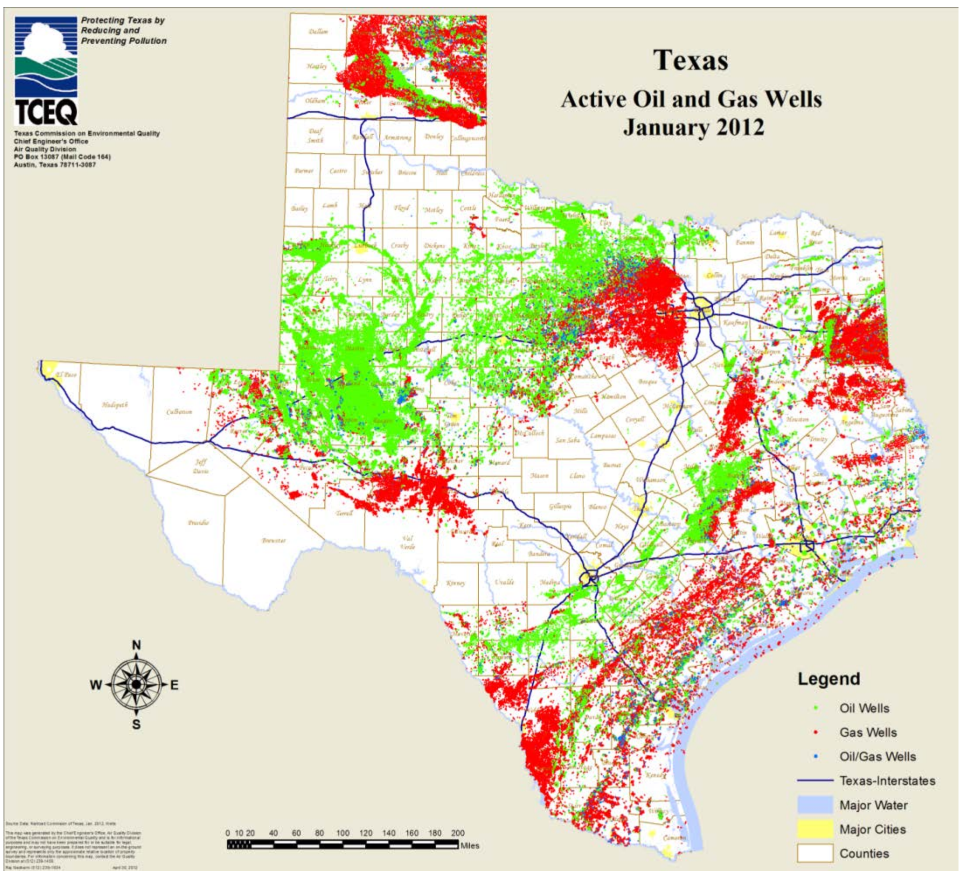
> *"In the Barnett Shale of North Texas, the combined VOC and NOx emissions from NG and oil production have been estimated to be comparable to those from the roughly 4 million cars and trucks in the adjoining Dallas-Fort Worth metro area"*. (Alvarez and Paranhos, 2012)

Chapter 2. Shale Gas and Shale Oil Plays[1] in Texas

The U.S. Energy Information Administration (EIA) reported that approximately 30% of total U.S. natural gas production occurs in Texas (*2*). Although natural gas is prevalent throughout Texas, there are certain areas that have significantly higher concentrations of hydrocarbons and hence are the major focus points for natural gas activity. The four main areas of natural gas are the:

- Anadarko Basin in the Texas Panhandle stretching into Oklahoma,
- Barnett Shale in the Dallas-Fort Worth-Arlington region,
- Bossier/Haynesville Shale of East Texas stretching into Louisiana, and
- The Eagle Ford Shale natural gas fields stretching from Webb to Anderson County.

Figure 2.1 illustrates the active oil and gas wells as of January 2012 in Texas.



Source: http://www.tceq.texas.gov/airquality/barnettshale/bshale-maps

Figure 2.1: Active Oil and Gas Wells in Texas as of January 2012

[1] In the context of shale gas exploration, a "play" refers to an area targeted for further exploration after favorable preliminary indications of oil or gas deposits.

The following sections provide a brief overview of the Anadarko Basin, Barnett Shale, Bossier/Haynesville Shale, and Eagle Ford Shale natural gas fields.

Anadarko Basin

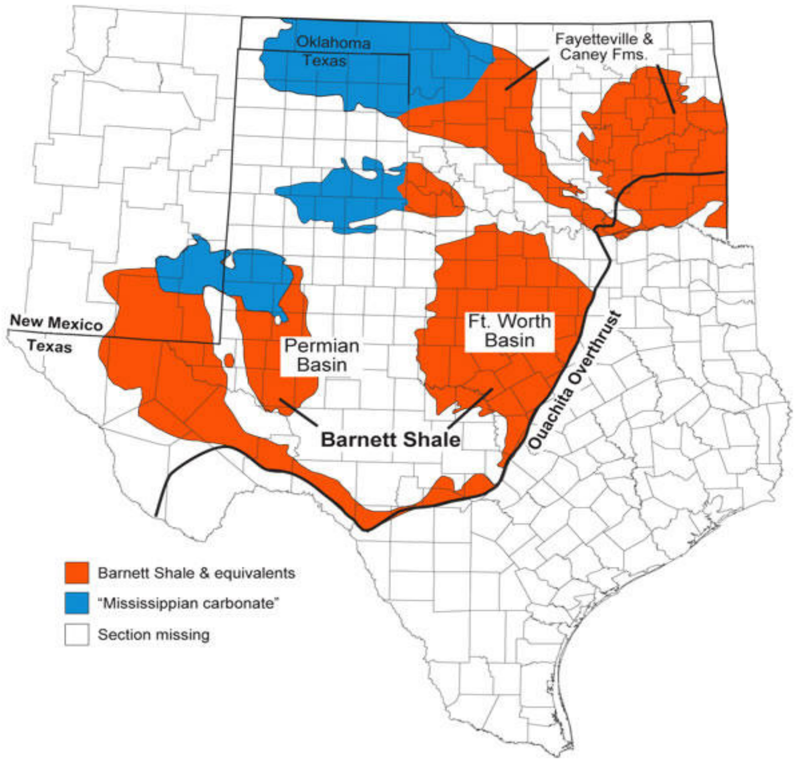
The Anadarko Basin, located in western Oklahoma, southwest Kansas, and the north Texas panhandle, is a geologic formation that stretches over approximately 50,000 square miles (see Figure 2.2). It is one of the major hydrocarbon-generating locations in the U.S. (*3*) The basin comprises sedimentary deposits of 2,000 feet in the north and west to 40,000 feet in the south. It is a large, deep, two-stage Paleozoic basin with rocks as thick as 12 kilometers that is rich in hydrocarbons. Significant oil and gas findings have been made in the area (*4*). Since the early 1900s more than 2.3 billion barrels of oil and more than 65.5 trillion cubic feet of natural gas has been produced in the basin (*5*). The total technically recoverable natural gas resources are estimated at 27.5 trillion cubic feet (*6*).

Source: http://familytreecorp.com/operations/anadarko-shale/

Figure 2.2: Anadarko Basin Location in North Texas

The Barnett Shale

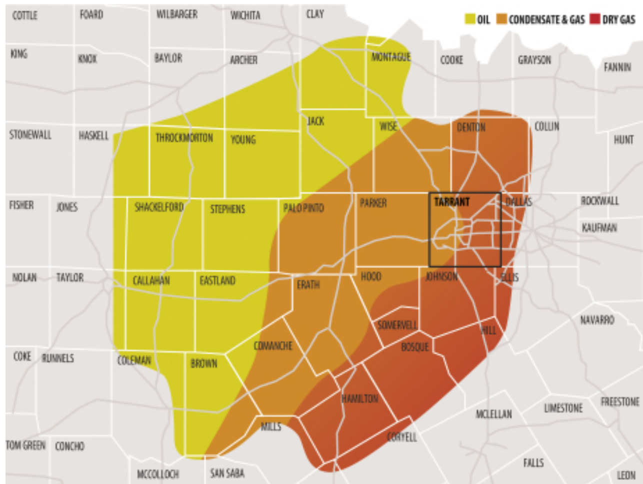
Barnett Shale gas in Texas is located in the Fort Worth and Permian Basins (see Figure 2.3).



Source: Airhart, ND (*7*)

Figure 2.3: The Barnett Shale

The Barnett Shale area in the Fort Worth Basin is a 19-county region of rapidly increasing natural gas production. It covers Clay, Cooke, Denton, Erath, Hill, Hood, Jack, Johnson, Montague, Palo Pinto, Parker, Tarrant, Wise, Young, Bosque, Comanche, Dallas, Somervell, and Hamilton counties (Barnett Shale Energy Education Council, ND). These counties are illustrated in Figure 2.4. Five of these counties - i.e., Dallas, Denton, Tarrant, Johnson, and Parker – are in violation of the eight-hour National Ambient Air Quality Standard for Ozone (*8*).



Source: http://oilshalegas.com/barnettshale.html

Figure 2.4: Barnett Shale Formation: Fort Worth Basin

The Barnett Shale area was first discovered by Mitchell Energy in 1981, but only became a significant producer of natural gas after advances in drilling technology in the mid-nineties allowed oil and gas producers to drill horizontally through the thick shale and after significant increases in the price of natural gas. Today, the Barnett Shale is one of the largest producing natural gas fields in North America.

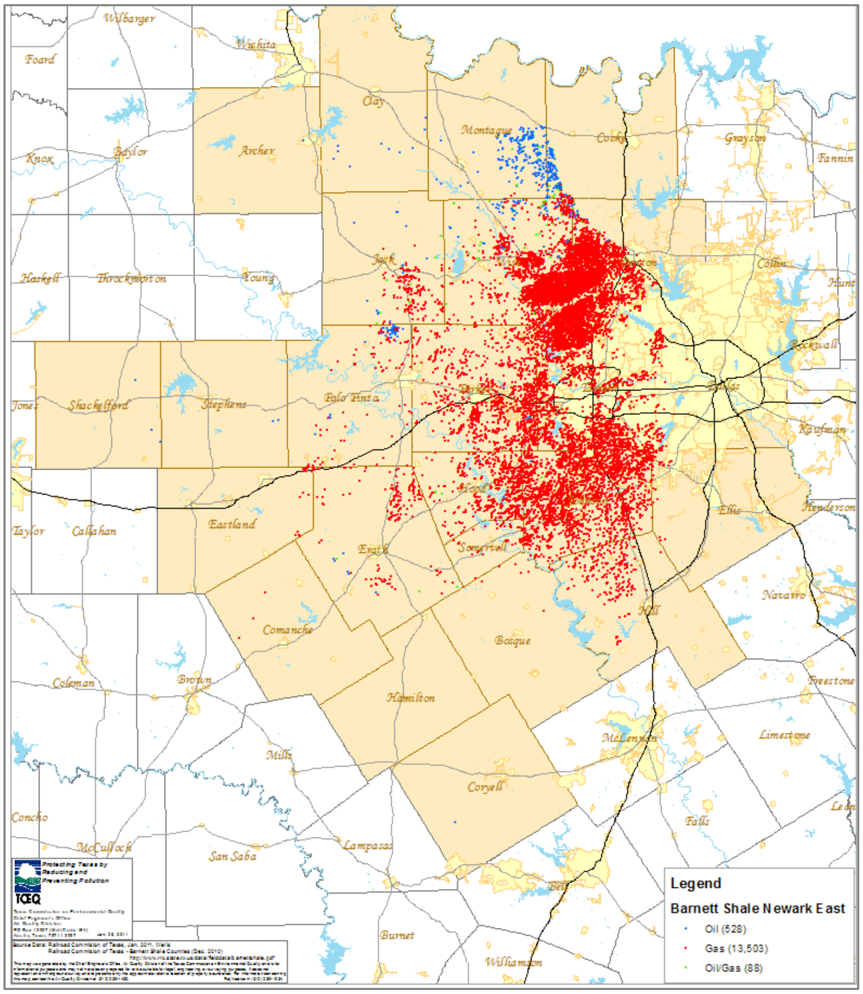
According to the U.S. Geological Survey (USGS), the Barnett Shale formation in the Fort Worth Basin covers an area of approximately 6,458 square miles (*9*) at depths of 6,500 to 8,500 feet with a thickness of 300 feet in the Fort Worth Basin. The total technically recoverable natural gas resources are estimated at 43.37 trillion cubic feet (*10*). Table 2.1 provides additional information about the Barnett Shale formation in the Fort Worth Basin.

Table 2.1: Barnett Shale Information (Fort Worth Basin)

	Active*	Undeveloped**
Area (Square Miles)	4,075	2,383
Estimated Ultimate Recovery (Billion Cubic Feet/Well)	1.6	1.2
Well Spacing (Wells/Square Mile)	5.5	8
Technically Recoverable Resources (Trillion Cubic Feet)	53.3	19.4

* The active area represents the area that is currently developed by companies.
** The undeveloped area is the area that has not been developed by companies.
Source: U.S. Energy Information Administration, 2011

In 2007, the Barnett Shale region (Fort Worth Basin) produced approximately 3.75 billion cubic feet of natural gas per day (*11*) and as of January 2010 there were approximately 14,000 wells in the area producing about 4.8 billion cubic feet of natural gas per day (*12*). Most of the production in the Barnett Shale area (approximately 80%) occurs within the Fort Worth-Arlington metropolitan area, specifically Denton and Wise counties. However, major metropolitan areas in Tarrant, Johnson, and Parker counties have also seen a significant increase in well development over the past several years. Figure 2.5 illustrates the location of the active gas wells in the Barnett Shale formation as of January 2011.



Source: http://www.tceq.texas.gov/airquality/barnettshale/bshale-maps

Figure 2.5: Active Wells in Barnet Shale Formation

The Barnett-Woodford shale gas play in the Permian Basin in West Texas covers an area of approximately 2,691 square miles at depths of 5,100 to 15,300 feet with a thickness of 4 to 800 feet. The total technically recoverable natural gas resources are estimated at 32.2 trillion cubic feet (*13*). Table 2.2 provides additional information about the Barnett Shale formation in the Permian Basin.

Table 2.2: Barnett Shale Information (Permian Basin)

	Active
Area (Square Miles)	2,691
Estimated Ultimate Recovery (Billion Cubic Feet/Well)	3.0
Well Spacing (Wells/Square Mile)	4
Technically Recoverable Resources (Trillion Cubic Feet)	32.15

Source: U.S. Energy Information Administration, 2011

Haynesville/Bossier Shale

The Haynesville/Bossier Shale is a hydrocarbon rich formation stretching over Shelby, Panola, Harrison, Marion, Rusk, and Nacogdoches counties in East Texas[2] and areas of Western Louisiana. Figure 2.6 presents a map of the Haynesville/Bossier Shale region in Texas.

Note: Most discoveries have been made in Harrison, Panola, and Shelby counties
Source: RRC, 2010

Figure 2.6: Haynesville/Bossier Shale

The Haynesville/Bossier shale play stretches over a total area of approximately 9,000 square miles at a depth of between 10,500 and 13,500 feet with a thickness of 200 to 300 feet. The total technically recoverable natural gas resources are estimated at 74.7 trillion cubic feet (*14*). Table 2.3 provides additional information about the Haynesville/Bossier shale play.

[2] Two of the counties – i.e., Rusk and Harrison – are included in the Northeast Texas (NET) Ozone Early Action Compact area (Texas Commission on Environmental Quality, ND).

Table 2.3: Haynesville/Bossier Shale Play Information

	Active*	Undeveloped**
Area (Square Miles)	3,574	5,426
Estimated Ultimate Recovery (Billion Cubic Feet/Well)	6.5	1.5
Well Spacing (Wells/Square Mile)	8	8
Technically Recoverable Resources (Trillion Cubic Feet)	53.3	19.4

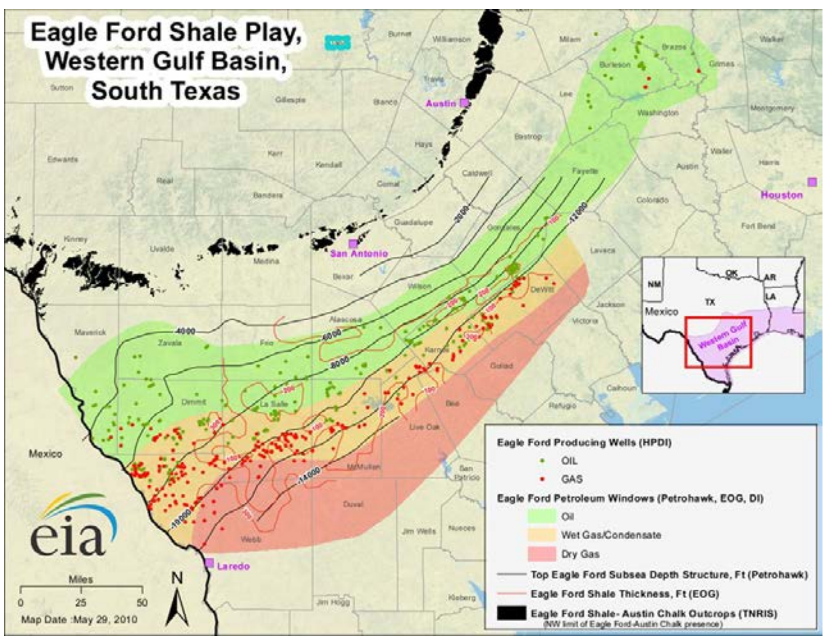
* *"The active area corresponds with the acreage that is currently held by the companies and might be under development".*

** *"The undeveloped area represents the acreage that is not currently held by companies".*

Source: U.S. Energy Information Administration, 2011

Eagle Ford Shale

The Eagle Ford shale formation, a vast network of rock layers, is believed to be one of the largest oil and gas fields in the U.S. The deep and dense shale formation runs about 400 miles from the Texas-Mexico border near Laredo, south of the San Antonio area[3], and into East Texas. The play is 50 miles wide and an average of 250 feet thick at a depth between 4,000 and 12,000 feet. The Eagle Ford shale play comprises three zones: an oil zone, a condensate zone, and a dry gas zone (see Figure 2.7). The shale contains a high amount of carbonate, which makes it brittle and thus easier to use hydraulic fracturing to produce the oil or gas (RRC, ND).



Source: http://www.eaglefordshale.com/eagle-ford-shale/attachment/eagle-ford-shale-map-1024x786/

Figure 2.7: Eagle Ford Shale Gas and Oil Play

3 Wilson County (south east of Bexar County) is part of the San Antonio Ozone Early Action Compact Area and Victoria County is in near nonattainment of the National Ambient Air Quality Standards. (Texas Commission on Environmental Quality, ND)

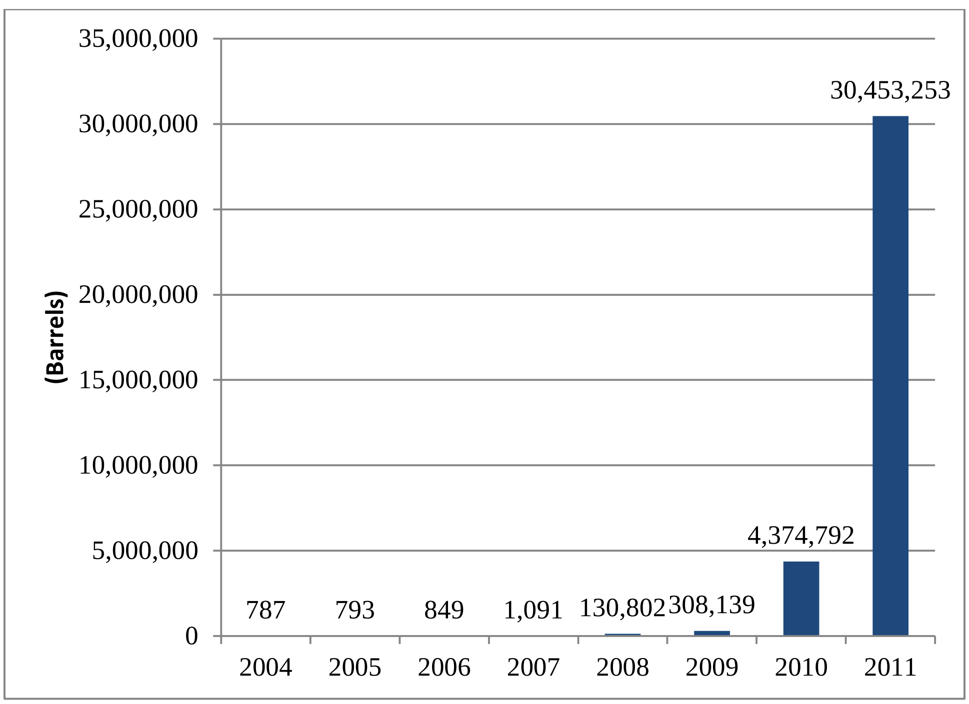
The area of the dry gas zone is estimated at 200 square miles, the area of the condensate zone at 890 square miles, and the area of the oil zone at 2,233 square miles. Table 2.4 provides additional information about the Eagle Ford shale formation.

Table 2.4: Eagle Ford Shale Information

	Dry Gas Zone	Condensate Zone	Oil Zone
Area (Square Miles)	200	890	2,233
Estimated Ultimate Recovery (Billion Cubic Feet/Well)	5.5	4.5	
Estimated Ultimate Recovery (Thousand Barrels of Oil /Well)			300
Well Spacing (Wells/Square Mile)	4	8	5
Technically Recoverable Resources (Billion Barrels of Oil)			3.35
Technically Recoverable Resources (Trillion Cubic Feet)	4.38	16.43	

Source: U.S. Energy Information Administration, 2011

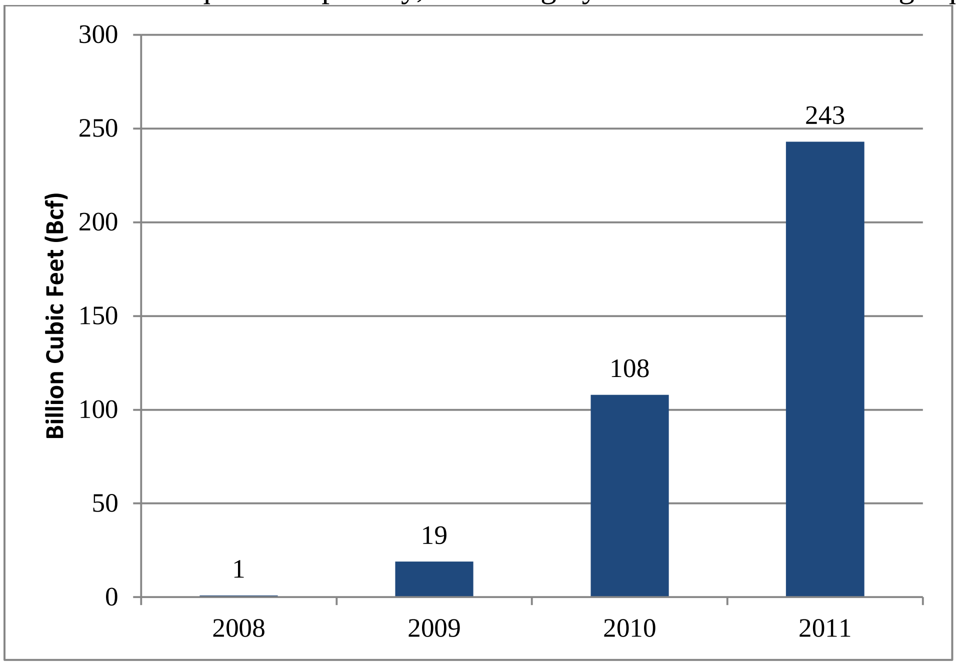
The Eagle Ford shale is a rapidly developing play. Figures 2.8, 2.9, and 2.10 illustrate the increase in oil, natural gas, and condensate production levels in the Eagle Ford shale play.



Source: Railroad Commission of Texas, ND (*15*)

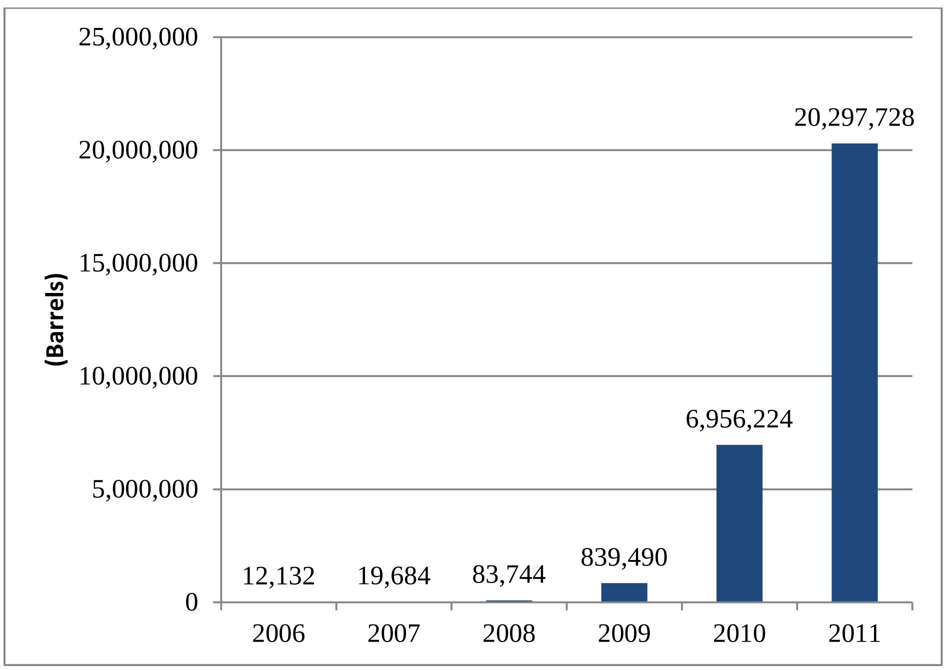
Figure 2.8: Eagle Ford Oil Production

By 2012, the oil output has increased 230-fold in three years, and this has boosted domestic oil production by 14% (*16*). It is estimated that by 2015, Eagle Ford production will reach 1.2 million barrels of oil equivalent per day, with roughly three fifths of that being liquids.



Source: Railroad Commission of Texas, ND (*17*)

Figure 2.9: Eagle Ford Shale Gas Well Gas Production



Source: Railroad Commission of Texas, ND (*18*)

Figure 2.10: Eagle Ford Shale Condensate Production

Concluding Remarks

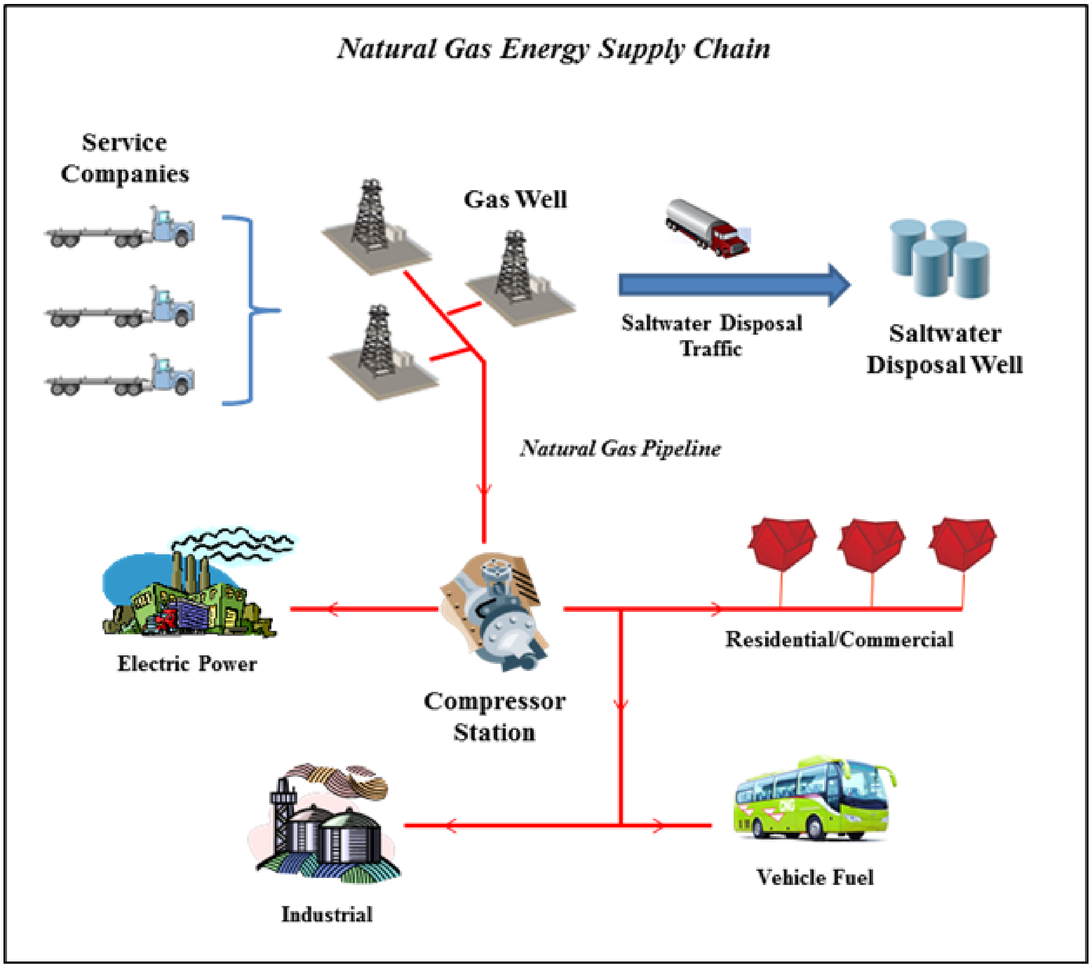
Natural gas has been promoted as a relatively clean fossil fuel that can play an important role in reducing pollution and ensuring energy security. This Chapter illustrated that Texas has significant shale gas reserves and that innovative technologies have facilitated increased natural gas production from unconventional natural gas fields such as the Barnett Shale and Eagle Ford Shale regions. The mining of these natural gas reserves undoubtedly contributes to the Texas economy through increased employment, business output, and tax revenues. On the other hand, concerns have been expressed about the impacts of increased natural gas mining on the state's infrastructure and natural environment. The latter is addressed subsequently in Chapter 3.

Chapter 3. Natural Gas Supply Chain

Natural gas production is a complex multi-stage operation that involves the collaboration of many entities. First, seismic exploration is conducted to determine the most economically suitable locations for drilling natural gas. Then a pad site and a site access road are prepared to move construction and drilling traffic. Afterwards, the rotary rig is delivered in several sections and assembled on site. Once the rig is assembled, drilling begins and the well site is continuously visited by service companies – e.g., cement and mud services - over a span of several weeks. If the well is determined profitable, a well head is installed and the well is connected to the main pipeline (*19*).

Typically, several wells are drilled on the same pad site and are connected to one main gathering line, which then connects to a compressor station. Compressor stations function similarly to electrical substations in that they act as central distribution points for natural gas. Natural gas flows through the well head to the pipe and into compressor stations where water vapor and other condensate is removed to ensure a higher quality product. Then higher pressure is applied to move the gas to local and distant markets through transmission pipelines. In the U.S., almost all natural gas (approximately 95%) is distributed from the well to its final destination through a network of pipelines. Truck, rail, or barge transportation of natural gas requires converting the gas into liquid form—which occurs at approximately -260° F—and hauling it in specially outfitted tanker units. Therefore, it is rarely transported via truck or rail (*17).*

Natural gas production thus consists of several major operations that impact (i) air quality (ii) the Texas transportation system, and (iii) potentially water quality. Figure 2.1 illustrates the natural gas supply chain and the major construction/production activities that comprise the mining and distribution of natural gas. This Chapter discusses the impacts (specifically, air and water quality) associated with well development and the production of natural gas, as well as air quality concerns that have been raised concerning the use of natural gas in vehicle fleets.



Source: Prozzi et al. 2011

Figure 3.1: Natural Gas Energy Supply Chain

Well Development

The five-step well development process comprises: site preparation, rigging up, drilling, hydraulic fracturing, and rigging down. Initial site preparation requires heavy bulldozers for grading and building a road to serve the pad site. Subsequently, the rotary rig must be moved to the pad site and assembled on site. Typically, a rig that can drill a 10,000 foot well will require 35 to 45 semi-trucks to move and 50 to 75 people to assemble the rig. Once the drilling of the well hole begins, steel piping and cement are delivered on site by truck for casing and cementing the well hole to prevent groundwater contamination. Mud used for lubricating the drill is also delivered on site by truck. Drilling of the well hole takes about 2 to 3 weeks. If the well hole is determined to be economically viable, the well is perforated using hydraulic fracturing (*20*).

The natural gas when extracted from the well is typically a mixture of various hydrocarbon gases. Although the composition of the natural gas can vary greatly, Table 3.1 provides a typical composition of unrefined natural gas (*19*).

Table 3.1: Typical Composition of Natural Gas

Component		Quantity
Methane	CH_4	70-90%
Ethane	C_2H_6	0-20%
Propane	C_3H_8	
Butane	C_4H_{10}	
Carbon Dioxide	CO_2	0-8%
Oxygen	O_2	0-0.2%
Nitrogen	N_2	0-5%
Hydrogen Sulphide	H_2S	0-5%
Rare Gases	A, He, Ne, Xe	trace

Source: Natural Gas Supply Association, ND (*21*)

The emissions associated with hydraulic fracturing as backflow water - which includes fraccing fluids, sand, and natural gas - emerges from the well may thus include: methane, volatile organic compounds (VOCs); particulate matter; $SO_{2;}$ carcinogens Benzene, Hexane, and Pyridines; neurotoxins xylene and carbon disulfide; and the blood poison naphthalene *(22, 23, 24, 25, 26*). A significant amount of methane can also be released during the well-completion stage – i.e., after the well is drilled yet before the well is connected to the main pipeline that will distribute the mined natural gas. Researchers at Cornell University have estimated that 1.9% of the gas produced by a typical shale gas well over its lifetime leaks during the fraccing and well-completion stage (*27*). Some states have rules that mandate the performance of green well completions and workovers, where rather than venting or flaring the gas, portable equipment is used to process and direct the gas into tanks or directly into the pipeline. These green completions on average recover 53% of the natural gas that would have been fugitive emissions (*20*). Emissions are also generated by drilling rigs that have engines fueled by diesel or natural gas, and fracturing operations that often use multiple diesel powered pumps[4] (*20,28).*

On April 17, 2012 the EPA issued rules that will require energy companies to capture natural gas emitted during the hydraulic fracturing of gas wells by January 1, 2015.

There is also air quality impacts that result from the transportation activities related to the drilling activities. Companies transport heavy equipment, pipes, water, sand, and chemicals to drilling sites. Well pads often contain multiple wells, and each well requires three to four million gallons of water, which are brought in by truck 5,000 gallons at a time. Finally, particulate matter

According to a study conducted by Texerra (2007), a typical well in the Barnett Shale area requires approximately 3.05 million gallons of water for drilling and hydraulic fracturing. If water from the local area is unavailable, it must be delivered to the well site by truck.

[4] The EPA has issued a number of environmental rules between 2010 and 2012 regarding air quality, emissions, water quality, and waste management that apply to the energy sector. The rules adopted apply to the production and processing of natural gas, natural gas transmission and storage and will reduce emissions from VOCs, air toxics, and methane – a greenhouse gas 20 times more potent that CO_2 (Environmental Protection Agency, 2012).

(PM) comes from (a) dust blown into the air during pad construction, (b) dust from vehicle traffic on access roads, and (c) from diesel exhaust from vehicles and engines.A Marcellus Shale field study, conducted by the New York State Department of Conservation, showed that the volume of truck traffic generated by the development of a single gas well can range from 295 to 455 truck visits (one way). The numbers are provided in Table 3.2 by construction activity.

Table 3.2: Truck Traffic Associated with the Construction of a Single Gas Well

Well Pad Traffic (1 Well)	Min	Max
Drill Pad and Road Construction Equipment	10	45
Drilling Rig	35	45
Drilling Fluid and Materials	25	50
Drilling Equipment (casing, drill pipe, etc.)	25	50
Completion Rig	15	15
Completion Fluid and Materials	10	20
Completion Equipment (pipe wellhead)	5	5
Hydraulic Fracturing Equipment (pump truck, tanks)	150	200
Hydraulic Fracture Sand Trucks	20	25
Total	**295**	**455**
Hydraulic Fracture Water	400	600
Total	**695**	**1,055**

Source: New York State Department of Environmental Conservation, 1998

As mentioned earlier, a single well is typically not drilled on a pad site. If a site is determined to be economically productive, then several wells may be drilled on the same site, followed by several more a couple of years later. Therefore, Table 3.3 presents construction traffic for a typical pad site where eight wells are drilled using two rigs.

Table 3.3: Truck Traffic Associated with the Construction of a Pad Site

Well Pad Traffic (8 Wells, 2 Rigs)	Min	Max
Drill Pad and Road Construction Equipment	10	45
Drilling Rig	60	60
Drilling Fluid and Materials	200	400
Drilling Equipment (casing, drill pipe, etc.)	200	400
Completion Rig	30	30
Completion Fluid and Materials	80	160
Completion Equipment (pipe wellhead)	10	10
Hydraulic Fracturing Equipment (pump truck, tanks)	300	400
Hydraulic Fracture Sand	160	200
Total	**1,050**	**1,705**
Hydraulic Fracture Water**	3,200	4,800
Total	**4,250**	**6,505**

Source: New York State Department of Environmental Conservation, 1998

From these statistics, the number of construction-generated truck trips in the Barnett Shale area can be estimated using well count data from the RRC's records. Using the minimum (i.e., 695) and maximum (i.e., 1,055) truck visit values for the construction of a single well on a pad site and applying it to the number of wells in the Barnett Shale as of January 2010, it can be estimated that construction traffic has generated ***9.7 to 14.8 million truck trips*** in the Barnett Shale region since commercial production of natural gas began in 2000.

To understand road usage and the average length of haul associated with well development traffic, Prozzi et al (2011) (*29*) conducted a route analysis using the TxDOT OS/OW permit database. The study team found that approximately 86.5% of all well development-related traffic included in the OS/OW dataset was local – i.e., the average trip length for hauling gas well equipment is 32.88 miles (standard deviation: 24.95 miles).

Natural Gas Production

Once natural gas production begins, a variety of activities emit air emissions. The primary emission sources include: compressor engine exhausts, condensate tank vents, production well fugitives, natural gas processing, and transmission fugitives (*30*). The emissions associated with these sources typically include criteria pollutants, such as nitrogen oxides (NOx), carbon monoxide, sulfur dioxides, particulate matter (PM), and unburned volatile organic compounds (VOCs) (*31*). Table 3.4 illustrates the number of emissions sources associated with different equipment used in natural gas production in the Barnett Shale area. This aids in illustrating the complexities involved in calculating emissions due to the exploitation of natural gas.

Table 3.4: Number of Emissions Sources in Barnett Shale Area

Emission Source	Number of Sources
Separators Vented to Atmosphere	52
Total Storage Tanks	22,764
Uncontrolled Glycol Dehydrators	111
Controlled Glycol Dehydrators	182
Total Stationary Engines	3,712
Turbines	37
Flares	78
Fractanks	20
Piping Component Fugitive Areas	17,553
Blowdown Vents	9,213
Process Vents	1,189
Heaters/boilers	900
Other Stationary Equipment	1,772
Total Emission Sources	**57,583**

Source: Oil and Gas Emissions Inventory (EI) Improvement Activities. TCEQ

The principal component of natural gas is methane (CH_4). Methane is known to be a powerful greenhouse gas and recent studies at the University of Colorado, Boulder and Cornell University have reported that natural gas wells leak much more methane into the atmosphere than previously thought *(32,33)*. As part of the imperfections of the processes, methane can be released as fugitive emissions, especially from equipment under high pressure such as pneumatic controls. Fugitive emissions from leaks in pipe connections and equipment are also possible. Some pneumatic instruments also release or bleed small quantities of natural gas as part of their normal operations. NOx are emitted from compressors or pumps needed to pump the gas to the surface or to pressurize the gas for the pipeline. Other emissions sources include flaring (NOx and CO) or blow down of gas in non-routine situations; dehydration units (VOCs) that are used to remove water from the produced gas; and sulfur removing systems such as flares or amine units *(5).* CO can be emitted as a result of burning carbon-based fuels in engines imperfectly, while SO_2 may be emitted when fossil fuels with sulfur are used in gasoline or diesel equipment. Finally, Ozone (O_3) can be formed from precursors VOCs and NOx in the presence of sunlight *(5).*

> *"Led by researchers at the National Oceanic and Atmospheric Administration (NOAA) and the University of Colorado, Boulder, the study estimates that natural-gas producers in an area known as the Denver-Julesburg Basin are losing about 4% of their gas to the atmosphere — not including additional losses in the pipeline and distribution system. This is more than double the official inventory, but roughly in line with estimates made in 2011 that have been challenged by industry."* (Tollefson, 2012)

There are also environmental impacts – both air quality and water quality - that result from the disposal of salt water during natural gas production. A natural gas well produces salt water throughout its life, referred to as *backflow*, which is typically trucked or moved by pipeline from natural gas well sites to Class II salt water disposal wells, where it is injected into porous rock deep underneath the earth's surface. The number of truck trips required to haul away the saltwater is largely dependent on the amount of water produced and the size of the truck. Data from Chesapeake Energy indicate that, on average, initial production of saltwater amounts to approximately 2,400 barrels per day, requiring approximately 16 truckloads to haul the salt water away. A typical water truck can transport between 5,000 to 6,300 gallons[5] of water per load. By the end of the first week, saltwater production decreases to approximately 1,096 barrels per day, requiring approximately 7 trucks to haul away. By the second week of production, water output drops by about 47% and after 60 days by about 72%. After 3 months, only one truckload per well per day is required to haul away the saltwater; after 6 months, the number drops to about one truckload per well per week. Although saltwater production continues to decline over time, the hauling of saltwater continues to be an issue throughout the life of a well. Based on the data from Chesapeake Energy, approximately ***395 truckloads*** will be required to haul away an estimated 2.13 million gallons of saltwater during fracturing and the first year of a well's production in the Barnett Shale region. A substantial share of the salt water trip occurs on lower functional road classes (e.g., local city streets and FM roads) and, in general, the haul distance averages about 9.4 miles (standard deviation: 5.34 miles) (*34*).

[5] One gallon of water weighs approximately 8.34 lbs and an average saltwater disposal truck can move up to 52,500 lbs of water.

Natural Gas Combustion

Natural gas is a comparatively clean fossil fuel when combusted. For example, the main products resulting from the combustion of natural gas are CO_2 and water vapor (see Table 3.5). The use of natural gas as an energy source in industrial applications, to generate electricity, and as a transportation fuel is thus seen as an option to reduce emissions and exposure to harmful pollutants.(*35*). Table 3.5 shows that the combustion of natural gas produces almost 30% fewer CO_2 emissions than oil and almost 45% *-fired [electricity] generation, natural gas produces half as much carbon dioxide, less than a third as much nitrogen oxides, and one percent as much sulfur oxides at the power plant"(36).* Natural gas usage is thus often promoted on the basis of its potential to reduce the U.S's share of greenhouse gas emissions, thereby reducing global warming.

Table 3.5: Fossil Fuel Emission Levels – Pounds per Billion Btu of Energy Input

Pollutant	Natural Gas	Oil	Coal
Carbon Dioxide	117,000	164,000	208,000
Carbon Monoxide	40	33	208
Nitrogen Oxides	92	448	457
Sulfur Dioxide	1	1,122	2,591
Particulates	7	84	2,744
Mercury	0.000	0.007	0.016

Source: EIA – Natural Gas Issues and Trends 1998 in Natural Gas Supply Association, ND

There has thus been a growing interest in the use of natural gas as a transportation fuel[6] (*37*) - also because of the vast resources, increased mining of unconventional shale plays, and due to high oil prices. In Texas, the Texas Clean Transportation Triangle - that encompasses the cities of Dallas-Fort Worth, Houston, and San Antonio – is a collaborative effort that aims to implement a natural gas transportation corridor. The effort is led by America's Natural Gas Alliance and comprises a strategic plan for the development of fuel stations that can support heavy-duty natural gas trucks and public and private natural gas vehicles (*38*). Although statistics on the number of natural gas vehicles operating in Texas are not readily available, some of the vehicle types that operate on natural gas in Texas include: buses, waste management trucks, larger Class 8 trucks, Class 2 (i.e., pickup trucks), vans, and Honda Civics. Some of these vehicles are bi-fuel vehicles, but most are reported to be dedicated natural gas vehicles. Some companies, e.g., AT&T and Verizon, have converted a substantial share of their vans to natural gas (*39*). Although it is generally believed that the adoption of natural gas as a transportation fuel in lieu of diesel and petroleum would result in a reduction in greenhouse gases, a number of studies have recently revealed contradictory findings. For example, Burnham and Clark (2012)

[6] Natural gas; however, has a lower energy density than conventional fuels and must be compressed or liquefied to be a viable transportation fuel. *"Compressed natural gas (CNG) typically takes about 1/300th of the volume of natural gas at standard atmospheric pressure. Liquefied natural gas (LNG) manages to reduce this to approximately 1/600th of the volume. Even at this volume, LNG is approximately 40 per cent less energy-dense than diesel (22 megajoules per litre vs 38MJ/L). As a result, natural gas vehicles have a shorter range or require a larger fuel tank."* (Gill and Coad, 2012)

reported no statistical difference in greenhouse gas emissions between petroleum-fueled vehicles and natural gas vehicles over a 100 year framework. More concerning, the authors reported 25% higher greenhouse gas emissions for natural gas vehicles relative to petroleum-fueled vehicles when evaluated over a 20-year framework (*40*). Concern has also been expressed about the tailpipe emissions and fugitive emissions associated with the venting of LNG storage tanks and tanker trucks. The latter concerns have been downplayed by the Clean Vehicle Education Foundation who has argued that venting will only occur under a worst case scenario when a vehicle has not been used over a number of days/weeks and even in this worst case scenario the total release would be minimal. Others have acknowledged that very small amounts of methane escape during the transfer of the liquefied natural gas (LNG) from the tank to the trailer and during the fuelling of the vehicles (*29).*The amounts; however, are believed to be small, but no robust study or reliable data are available.

Concluding Remarks

Natural gas is generally considered a *"cleaner fuel"* than oil and gas, but recently researchers have started to question the lifecycle emissions benefits of natural gas. In other words, whether emissions and greenhouse gas reduction benefits associated with natural gas usage outweighs the emissions emitted during natural gas production and distribution – specifically leaked methane, which is a much more potent greenhouse gas than CO_2 – relative to the usage of oil. For example, one study argued that the leakage in getting the gas from the wells to compressed natural gas (CNG) vehicles currently results in the use of these vehicles contributing to more climate change than if these vehicles used gasoline (*41*). On the other hand, it has been reported that not all studies support these higher emissions numbers (*42*). The literature is thus rather inconclusive about the air quality impacts associated with natural gas production and usage.

Chapter 4. Summary and Conclusions

Although natural gas is considered a relatively cleaner fossil fuel compared to oil and coal, a number of studies have started to illustrate the traffic, water, and air quality concerns associated with natural gas production and distribution, while concerns have also been raised about fugitive and tailpipe emissions from the use of natural gas vehicles. This report provides an overview of Texas's natural gas reserves, describes the elements of the natural gas supply chain, and the environmental (air and water quality) concerns associated with each element of the natural gas supply chain.

The traffic and associated impacts on Texas's transportation system associated with natural gas mining and production have been studied in two recent TxDOT Research Studies and is also the focus of a recently formed Task Force on Texas' Energy Sector Roadway Needs. It has been estimated that the construction a single well on a pad site requires between 695 and 1,055 truck visits. In addition, approximately 395 trucks will be required to haul away saltwater resulting from the hydraulic fracturing process (i.e., backflow) and from a well's production in the first year in the Barnett Shale area. Most of these trips are local - i.e., the average trip length for hauling gas well equipment is 32.88 miles and for hauling saltwater is 9.4 miles. Although substantial in terms of the traffic generated when considering that 14,000 wells have been drilled in the Barnett Shale as of January 2010, it is believed that the associated emissions generated by this traffic pales in comparison to the emissions generated by the well development process (e.g., fraccing process and well completion), natural gas extraction, storage, and distribution. On the other hand, quantitative estimates of the air and water quality concerns associated with each element of the natural gas supply chain are largely inconclusive and points generally to a need for more robust data collection and analyses.

Improved data and additional research is needed to reduce uncertainty associated with quantifying emissions associated with natural gas mining, distribution, and use. The latter is especially important in Texas where some of these shale formations are located in nonattainment and near-attainment areas in the state. Intensive natural gas extraction can worsen the air quality in nonattainment areas, thereby impacting ongoing monitoring, or could result in areas of near-nonattainment becoming in violation of National Ambient Air Quality Standards. Some data will become available given the requirement for the oil and natural gas industry to report greenhouse gas emissions under the EPA's mandatory greenhouse gas reporting program and given the implementation of the new EPA emissions standards for the oil and natural gas sector in 2015. However, the need for field data and analysis seems to persist to quantify emissions associated with natural gas extraction from shale formations.

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